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A COMPUTERIZED ACOUSTIC IMAGING TECHNIQUE INCORPORATING AUTOMATIC OBJECT RECOGNITION

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ABSTRACT

A computerized technique combining backward wave propagation and an automatic edge detection scheme has been developed and tested. The class of objects considered is limited to those with edge boundaries since it can be shown that a universal automatic reconstruction scheme cannot be obtained for all possible objects. Using samples of the acoustic diffraction pattern as input data, this technique enables the computer to predict the most likely locations of objects and to produce graphical output of the objects. A simplified edge detection scheme conserving both memory space and computer time was used. Test results are presented for both computer generated diffraction patterns and one set of experimental data.

INTRODUCTION

The existence of linear ultrasonic transducers that can directly record the amplitude and phase of an ultrasonic field leads to the presence of many imaging techniques that have no analog in optics. One such technique is "backward wave propagation".[1,2,3] In this technique the

ultrasonic field is sampled in both amplitude and phase by a scanning transducer or a transducer array. This information is then given to a computer for processing. The diffraction equations are programmed in the computer and the input data is processed to produce two-dimensional cuts in a volume defined by the program. Hence perfect reconstructions are possible only for planar objects. The results of trying to reconstruct a three-dimensional acoustical object are identical to observing the real image in the reconstruction of an optical hologram. The shape of a three-dimensional can only be reconstructed in a series of sections through its real image. Of course, other difficulties[4] attendant to computerized imaging techniques are also present (e.g. quantization errors, limited memory space, scan nonuniformities, etc.).

One of the greatest drawbacks of digital reconstruction is that the distance from the hologram to the object must be known for use in the diffraction equations. In optical holography this problem never occurs in the case of visual reconstruction of an object from its virtual image because the focus is found automatically by an eye-brain interaction. Similarly in scanning the visual real image with a screen, it is the eye-brain interaction that provides feedback to decide the optimum location for the screen for maximum object recognition and focus. The highly complex interaction between the eye and brain is not presently amenable to computer simulation. Nevertheless it would be of great help to find a method which brings about automatic focusing of the digital reconstruction or at least narrows down the region in space where the image is located. To conserve operator time and effort, it is desirable to have the computer consider the images of all cross-sections that it calculates to decide the most likely position or positions of image location and present only those images for operator consideration and object identification. In this study it is assumed that the medium of propagation is linear and not disturbed by turbulence or convection.

In programming the propagation equations, a spatial frequency approach [5] has been used rather than a straight forward programming of the Fresnel or Fraunhofer integral propagation relations. Use of this technique has the advantages of efficient algorithms such as the Fast Fourier transform (FFT) [6] and a wide flexibility of propagation distances since no assumption on distance is made as in the Fresnel or Fraunhofer approximations.

BACKWARD WAVE PROPAGATION

To summarize the technique of backward propagation in terms of the spatial frequency approach we consider a given complex valued diffraction pattern $\underline{U}_0'(x_0, y_0)$ located in plane a distance z from an object $\underline{U}_1(x_1, y_1)$. The spatial Fourier transforms $\underline{U}_0'(f_x, f_y)$ and $\underline{U}_1(f_x, f_y)$ of the patterns are related by [5]

$$\underline{U}_0'(f_x, f_y) = H(f_x, f_y) \underline{U}_1(f_x, f_y) \quad (1)$$

where $H(f_x, f_y)$ is the transfer function and is given by:

$$H(f_x, f_y) = \exp \left[j \frac{2\pi z}{\lambda} \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} \right] \quad (2)$$

For spatial frequencies such that $(\lambda f_x)^2 + (\lambda f_y)^2 < 1$ the transfer function is a phase shift. For $(\lambda f_x)^2 + (\lambda f_y)^2 > 1$ the transfer function behaves as a negative exponential, and the corresponding waves (called "evanescent waves") decay after propagating a few wavelengths. Hence, the propagation transfer function is often written in bandlimited form for propagation distances greater than a few wavelengths:

$$H(f_x, f_y) = \begin{cases} \exp \left[j \frac{2\pi z}{\lambda} \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} \right] & \text{if } f_x^2 + f_y^2 < \frac{1}{\lambda^2} \\ 0 & \text{elsewhere} \end{cases}$$

(3)

The reverse propagation problem is attacked by solving the transfer relation Eq. (1) for the object given the diffraction pattern

$$U_1'(f_x, f_y) = H^{-1}(f_x, f_y) \underline{U}_0'(f_x, f_y) \quad (4)$$

where H^{-1} is defined by the relation $H H^{-1} = 1$. Hence

$$H^{-1}(f_x, f_y) = \begin{cases} \exp\left\{-j\frac{2\pi z}{\lambda} \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2}\right\} & f_x^2 + f_y^2 < \frac{1}{\lambda^2} \\ 0 & \text{elsewhere} \end{cases} \quad (5)$$

It is important to note that the information contained in the evanescent waves has been irretrievably lost as these waves die out (assuming propagation distances of at least several wavelengths). Since this information contributes to the image, we can never expect a perfect reconstruction of the object using backward propagation. A theoretical discussion of this problem is found in Ref.7.

The computer programming of Eq.(4) to accomplish the backward propagation consists of:

- (1) Taking the discrete Fourier transform of the input data with the FFT.
- (2) Multiplication by $H^{-1}(f_x, f_y)$ at a given distance z .
- (3) Taking the inverse Fourier transform of the result to find the acoustic field at that distance.

OBJECT RECOGNITION

Given that the diffraction pattern can be backward propagated to any plane, a technique is now required to determine if the computed diffraction pattern corresponds to an object in that plane. At this point it is necessary to make some

assumptions about the object since without them there is no reason to favor the reversed diffraction pattern at the object plane over that obtained at any other location.^[8] In this study we chose to search for objects that had edges, i.e. connected regions where the acoustical amplitude underwent a sharp increase from some background level. Although this assumption provides a limitation on the class of objects that can be recognized (e.g. separated point sources or line objects cannot be recognized), the class of objects is of enough interest to warrant investigation. Because of the quantization of dimensions, the smallest object that could be detected is composed of four sampling points of high intensity next to each other, arranged in a square. This is not a severe requirement since it implies detection of at least all of one wavelength by one wavelength objects if the Nyquist sampling rate is used.

Existing detailed edge detection computer codes were applied to the problem but were found to take an inordinate amount of time to investigate each plane of the volume of interest. Hence a simple intuitive scheme^[8] was devised and implemented. In essence this edge detection scheme scans the plane of interest and determines the points associated with large changes of amplitude. An investigation is then made to find if these points are connected. A numerical index is kept which increases as more connected points are found. The planes are then ranked by the value of this index and the corresponding diffraction patterns are presented for operator inspection beginning with the highest value. The number of planes presented or the maximum difference in the numerical index in the presented patterns can be operator-controlled to optimize the number of planes presented.

It should be noted that in seeking objects with edges that it is not enough to just find the plane that has the maximum change in amplitude between adjacent points. For example, a lens surrounded by an opaque aperture will produce the

maximum amplitude change at its focal point if illuminated by a collimated beam. A technique incorporating an edge detection scheme will have a higher edge detection index in the lens location than at the focal point (as demonstrated in a case considered below) because of the higher weighting given to connected points.

The concept was tested using many computer generated diffraction patterns and one sample of experimental measurements. The Fourier transform and propagation algorithms were tested using simple patterns and comparing the results with theoretical results. Test cases of varying complexity were then applied to exercise the program.

COMPUTER GENERATED TESTS

The simplest object was a 16λ by 8λ rectangle of unit amplitude against a zero amplitude background. All sample points in the object were in phase thus simulating a specular object or an illuminated slit. The diffraction pattern was calculated over a 32λ by 32λ observation plane (the same in all cases) at a distance of 175.3λ in front of the object. The data was introduced to the imaging program and the volume between 160λ and 192λ (from the diffraction data plane) was searched. The reconstruction (Fig. 1) was obtained at 175.25λ in 2.6 minutes.

The same object was also used with a background that had a uniformly distributed random amplitude between zero and .2 of the object amplitude and a uniformly distributed phase between zero and 2π radians. The diffraction pattern was calculated at a distance of 177.2λ . Using the imaging program, the reconstruction of Fig. 2 was found in 2.6 minutes. The position was in error by $.05\lambda$.

A similar object was used in another test case with a parabolic phase distribution added, thus simulating a cylindrical lens against a noisy background. The equivalent focal length

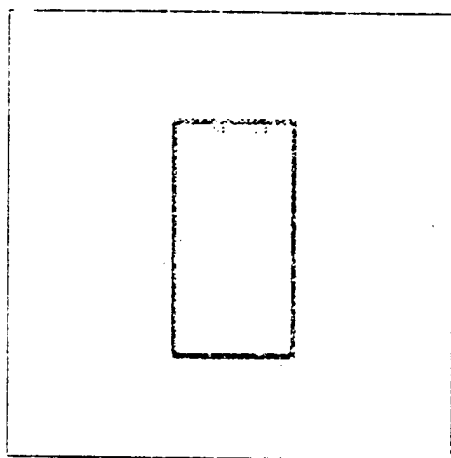


Fig. 1. Amplitude contour plot of reconstructed 16λ by 18λ rectangle.

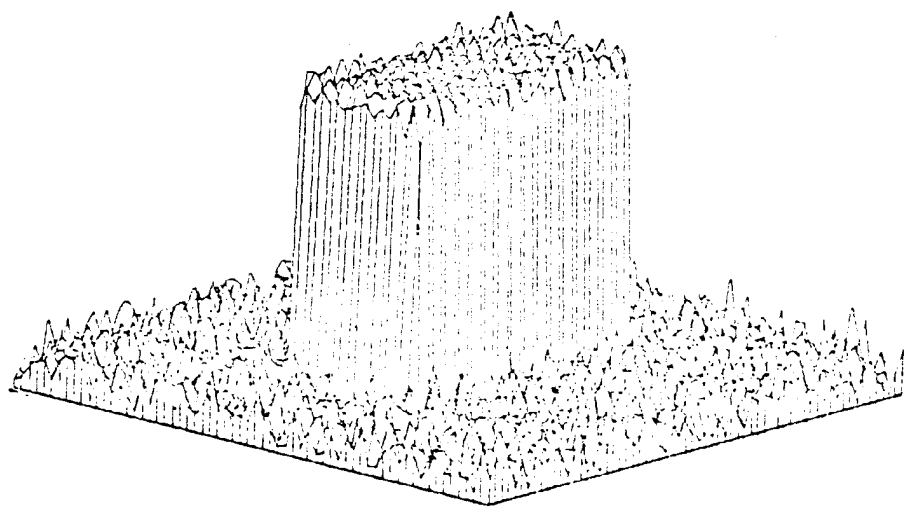
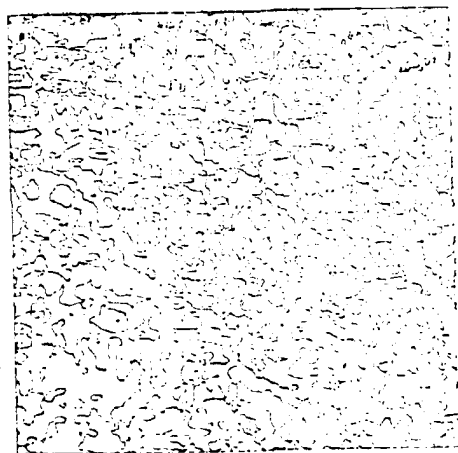


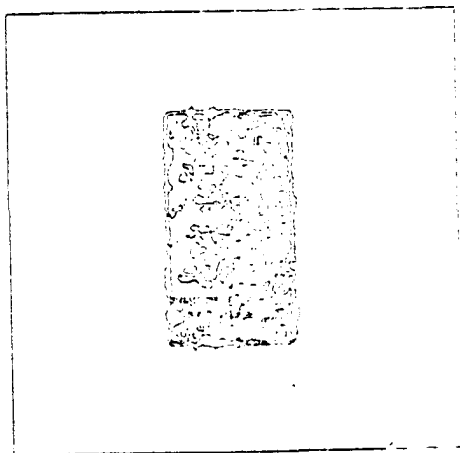
Fig. 2. Surface plot of amplitude of reconstruction of rectangular object against random background.

of the lens was 10λ . Using a diffraction pattern calculated at 177.1λ the correct reconstruction was accurately found in 3.3 minutes. The focal line was ignored (since the algorithm is insensitive to line objects).

A case was run where the object was a 16λ by 8λ rectangle with a uniformly distributed random amplitude varying between .8 and 1.0 and a uniformly distributed random phase between 0 and 2π . The background also was random with parameters as described in the previous cases. The diffraction pattern was calculated at a distance of 177.5λ . With this pattern the computer predicted two possible locations at 177.5λ and 163.75λ . The edge detection index of the first was 1.5 that of the second. If the operator were not confident of the differences in the index, a cursory inspection of the images (Figs. 3a and 3b) would give the correct object location.



(a)



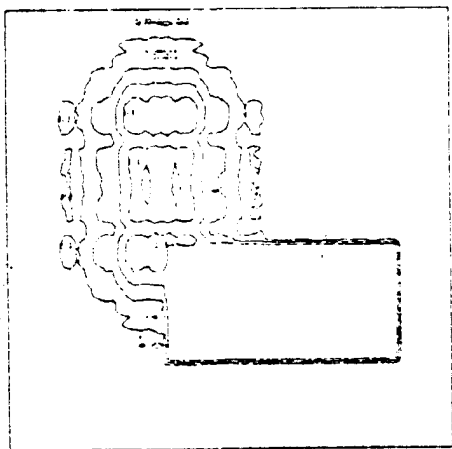
(b)

Fig. 3. Reconstructed images from random amplitude and phase rectangle at a) erroneous location and b) correct location.

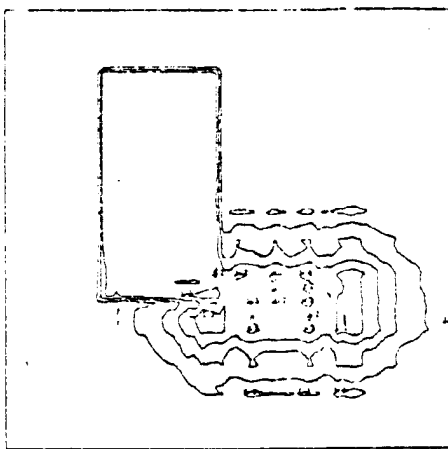
Planar objects of other configurations and sizes were also investigated and easily detected.

The next set of tests consisted of trying to reconstruct objects existing in two parallel planes. Since the real image is constructed in backward wave propagation, one difficulty is obvious--in the planes of the object there will be indications of the second out of focus object (Fig. 4a and 4b). The images are similar to the twin images of an in-line hologram and require more operator interpretation.

The simplest object was two 16λ by 8λ rectangles with unit amplitude and all sample points inphase. The objects were 15λ apart, and one rectangle was oriented 90° with respect to the other with a 10% overlap. The diffraction pattern was calculated 100.4λ from the front rectangle. Inspecting a volume 45λ deep, the computer took 8.5 minutes to locate the front (Fig. 4a) and back (Fig. 4b) rectangle within $.15\lambda$ of their actual location.



(a)



(b)

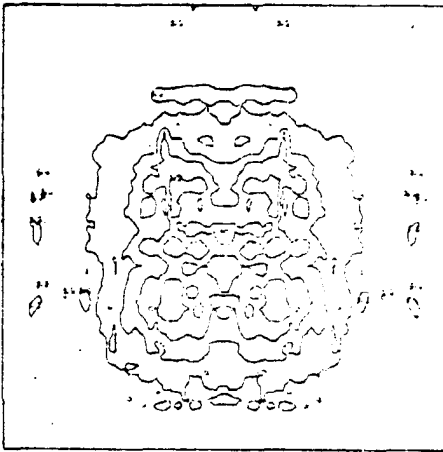
Fig. 4. Reconstruction of double rectangle object at a) plane of front rectangle and b) plane of back rectangle.

Other tests of varying spacing and degrees of overlap were conducted.^[8] In the complicated patterns it was found helpful to find and define the front object first and then subtract that object from the diffraction pattern in the front plane. Using the altered pattern as data, the second object location could then be found more quickly by the computer and understood more easily by the operator. It is noted that part of the back object was obscured by part of the front object in these tests; hence recognition of the back object was more difficult for the operator. Also the assumed perfect coherence of the sound and the subsequent interference of the waves from the two objects complicates the recognition pattern. It was, of course, observed that the processing time increased with the complexity of the object.

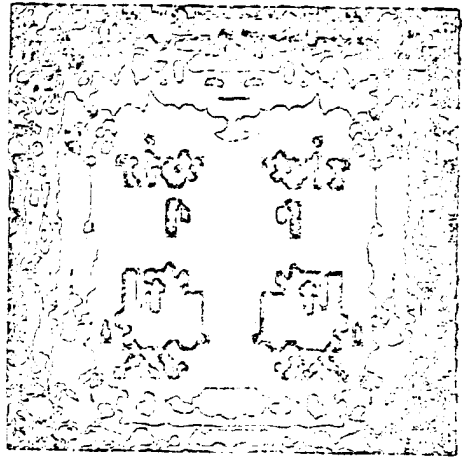
TEST WITH MEASURED DATA

In a final test a set of experimental data from an actual diffraction pattern was used. The pattern (which was originally used for a different purpose) was recorded at an approximate distance of 73λ from a square edge-clamped transducer with an active area of 4.5 cm by 4.5 cm at a frequency of 1 MHz. To conserve recording time approximately one-half of the pattern was recorded and folded symmetrically. This results in an unnatural symmetry in the input (Fig. 5) and output data. Another fault with this set of data is that the sampling increment was $.9\lambda$ rather than $.5\lambda$; i.e. the sampling was performed at a rate below the Nyquist rate. Aliasing effects are therefore to be expected, mostly at high spatial frequencies leading to some distortion of the edges. Despite these faults the data was used since it was readily available on tape. An improved sampling unit is presently under construction that will eliminate these problems.

A volume between 60λ (from the input data phase) and 80λ was investigated in 4.4 minutes. Two possible object locations were found at 74.66λ



(a)



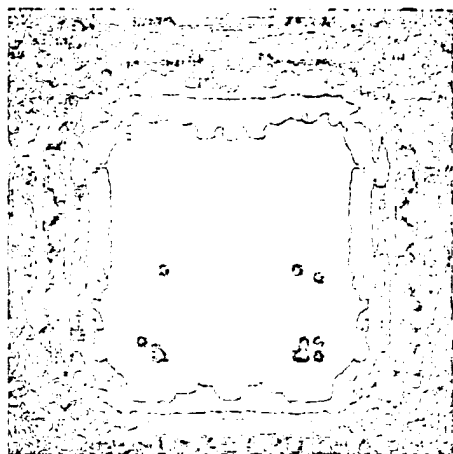
(b)

Fig. 5. Contour plot of experimental input
a) amplitude data and b) phase data of
square transducer.

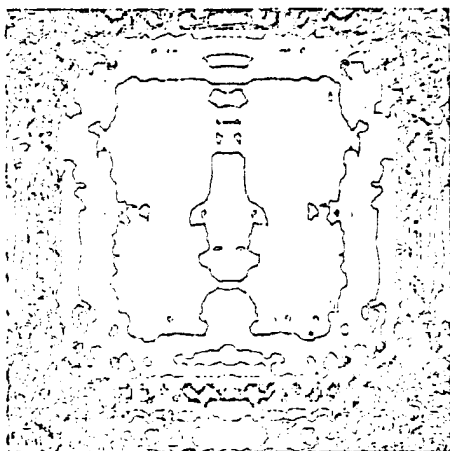
(edge measure index of 29.9) and at 67.68λ (edge measure of 26.4). It is noted that the higher edge measure corresponds to the measured location that was a nominal distance of 73λ . Since we are in the very near field of the transducer, the amplitude of the diffraction field does not change very much with distance, and the amplitude patterns at the two locations to a large degree is the same as the input data (Fig. 5a). The phase patterns, however, change rapidly in the near field. It is seen in Fig. 6a that all points on the transducer face have the same phase (or very nearly so) while in Fig. 6b (in front of the transducer), a distinct variation can be observed. Hence even with the flawed data, a general corroboration of the technique is supplied. More comprehensive tests with better data is proposed for the future.

SUMMARY

Based on these experimental and computer results it appears that the techniques of incorporating edge detection into a backward propagation computer code can provide an automatic reconstruction from sampled data. Processing times



(a)



(b)

Fig. 6. Contour plot of reconstructed object phase at a) object location and b) erroneous location.

quoted are indicative of handling 64 by 64 complex valued arrays using the Fast Fourier transform and our edge detection scheme. Improvements could be made to improve the efficiencies of both the FFT and edge detection program as no extraordinary effort was made to optimize these algorithms beyond achieving run times on the order of minutes. Generally speaking however, results presented are quite encouraging as they show that for many situations the computer can indeed make correct decisions as to the object location.

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